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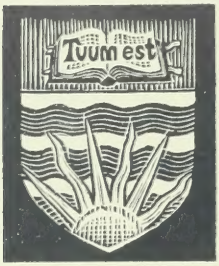

THE UNIVERSITY OF
BRITISH COLUMBIA

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

FOREST PRODUCTS RESEARCH

TECHNICAL PAPER No. 1

THE MOVEMENT OF MOISTURE

WITH REFERENCE TO

TIMBER SEASONING

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FOREST PRODUCTS RESEARCH

TECHNICAL PAPER No. 1

THE MOVEMENT OF MOISTURE

WITH REFERENCE TO

TIMBER SEASONING

By S. T. C. STILLWELL, B.Sc.

(*Officer in charge, Section of Seasoning*)

LONDON: PUBLISHED UNDER THE AUTHORITY
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FOREWORD

MUCH work has been carried out in different countries to determine the best methods of either air seasoning or seasoning timber by artificial methods, as unless timber can be reduced to an air-dried state without serious degrade it is of little value. Many and varied have been the designs of kilns or heating chambers devised to season timber artificially, many of which are based on sound principles, and give fair to satisfactory results. The position may be summarised by saying that the line of attack to solve the question of seasoning timber has been, from a practical point of view, based on a few general well known facts in connection with the drying out of timber, but that the information available as to the movement of moisture in timber after the tree is felled has not received the same amount of attention as the actual loss in moisture during the process of evaporation.

The experiments carried out by Mr. Stillwell aim at ascertaining what actually occurs in the timber during the process of evaporation, in so far as moisture movements are concerned, and it requires little foresight to understand that a further knowledge on the subject may lead to important modifications in seasoning timber on a commercial basis.

Due to the limited amount of information available, the investigation carried out was naturally of a preliminary nature, and clearly demonstrates the physical difficulties met with in obtaining reliable data, but the experience gained will be invaluable when carrying out further work on these lines. Not the least of the difficulties in such experimental work is the fact that the structure of timber is very complex, and varies not only in different species but from inch to inch in any individual specimen of one and the same species.

It is thought that the results so far obtained by working on the lines adopted by Mr. Stillwell are sufficiently promising to justify further investigation. By repeating some of the experiments, and by introducing a variety of species whose structure and arrangement of elements follow typical formations, it is hoped that definite data will be available on which to form concrete ideas as to the influence of structure on moisture movements.

R. S. PEARSON,
Director of Forest Products Research.

March, 1926.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH,
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CONTENTS

PAGE

Introduction 1

I. Account of Experiments made to investigate the Passage of Moisture through Timber 2

Rate of Passage of Moisture through Timber Plugs 2

Moisture Content Values of Timber when in Equilibrium with Certain Conditions of Temperature and Humidity 10

Moisture Gradient Experiments 12

The Passage of Air through Oak 14

II. A Suggested Explanation of the manner of Moisture Movement in Timber at a Content below Fibre Saturation Point 17

III. The Experimental Results 20

IV. Notes on the Experiments as Suggestions for Further Work 28

THE MOVEMENT OF MOISTURE WITH REFERENCE TO TIMBER SEASONING

INTRODUCTION

DUE to the work of the United States Forest Products Laboratory and other institutions carrying on similar investigations, the practice of kiln drying timber has been established, not only as an equal of the older air seasoning method, but as a process superior for nearly every purpose.

Schemes of treatment, by which a very wide variety of timbers can be successfully kiln-seasoned, have been determined experimentally. These, although they vary considerably in the details of temperature and humidity conditions recommended for use with different timbers, have the same basic form. The reason for this is that while the details for each individual timber have been worked out by actual experiment, the form of schedule is based on a knowledge of the conditions which cause and control moisture movement in converted timber generally.

While the success which has attended the present form of schedule goes far to support the correctness of the conclusions on which it is founded, it cannot be said that these are very precise, or complete ; in fact, this is far from being the case. Little more is known than that, in general, movement of moisture takes place between two adjacent points when there is a difference of temperature, or of moisture content, from one to the other.

Precisely how the movement takes place, and the exact quantitative relations between moisture movement and the temperature or moisture content difference are not known, nor, of course, the extent to which the movement may be affected by the structure of the timber.

With the view to obtaining more detailed information on these points, which must concern the process of kiln-seasoning fundamentally, a number of experiments described in the following pages were carried out. In spite of their preliminary nature, and the small field covered, they may have a value in showing not only what difficulties were met with, but also what success, for some of the results were very satisfactory, when the varied nature of the material used is considered.

Hence in the first part, an account of the experiments made, methods, and difficulties is given.

A large number of experiments of linear flow on oak were made before any possible explanation of the results obtained was arrived at. It then became clear that, in certain aspects, the experimental results could be accounted for by assuming the movement of moisture, at content below fibre saturation point, to take place in two ways ; one movement in the wood substance itself and the other as a diffusion across the contained air spaces, the two being related by a condition of equilibrium in any plane normal to the flow.

The second part of the paper is therefore concerned in a discussion of this matter, and the development of a semi-empirical equation relating flow and vapour pressure gradient, to which to apply the experimental results obtained.

In the third portion the experimental results obtained are applied to this formula, and, lastly, a few brief notes as suggestions for further work are added.

PART I.—ACCOUNT OF EXPERIMENTS MADE TO INVESTIGATE THE PASSAGE OF MOISTURE THROUGH TIMBER

Rate of passage of moisture through timber plugs

THE first experiments were carried out with a piece of thin oven-dried wood, coated on one face with anhydrous copper sulphate powder. The powdered face was kept dry by a sheet of glass, and the other was held tightly to the mouth of a vessel containing water. The vapour passing through the timber changed the colour of the powder, but so slowly that it was impossible to determine the exact time of first discolouration. This method was quickly abandoned, as too indefinite.

A second form of apparatus was more successful, and is, in fact, still used.

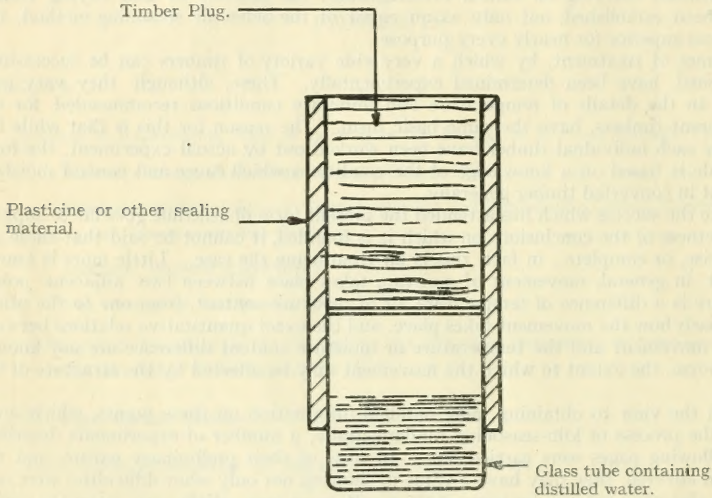

FIG. 1.

A cylindrical plug of timber was sealed over the open end of a short glass tube, the other end of which was closed. The internal diameter of the tube, generally about 1–1¼ inches, was the same as the section of the plug. Difficulty was at first experienced in making a good joint between plug and tube, but this was finally overcome by the following method. Much care, however, was always necessary.

The glass tube was washed in methylated spirits, and the outside coated from the mouth nearly to the base with a solution of shellac in methylated spirit. The outside of the timber plug, omitting the ends, was also given several coats of shellac, each being allowed to dry thoroughly. The plug was then held to the mouth of the tube, and fixed there by a heavy continuous coating of resin, lamp black, and linseed oil mixture, extending the full length of the plug and a half inch or more down the tube from the mouth. Finally this coating was in turn given several layers of shellac solution before use. A sketch of the plug and tube is given in Fig. 1.

In using the plug for experiment, the glass tube was partly filled with water before the two were fastened together. The plug and tube were then placed upright in a jar containing an aqueous solution of sulphuric acid of known strength, the base of the tube being raised above the level of the surface of the acid. The jar in turn was kept in an incubator, the temperature of which could be maintained very nearly constant.

The rate of transfusion of moisture through the plug due to the difference of vapour pressure at its two faces was measured by removing and weighing the plug and tube at intervals.

The first experiments carried out on a related series of plugs may now be described in some detail.

A carefully chosen piece of straight grained air-dried oak 7 in. long was cut down to 1·22 in. diameter amd coated with shellac, except at the ends. The piece was then cut into the following lengths in the order named :—

No. 1	2·00 in.
No. 2	1·50 in.
No. 3	0·99 in.
No. 4	0·75 in.
No. 5	0·50 in.

Each was carefully sealed to a tube containing water and placed in a desiccator, containing concentrated sulphuric acid, inside the incubator chamber, and there kept at a temperature of 30° C. Weighings were made at intervals and the rate of loss of weight in grams per 24 hours noted.

Ultimately the rate of moisture passage through each plug became approximately constant. In spite of precautions taken, however, in the case of the plugs with the moisture passage along the grain the flow from day to day varied to some extent, possibly due to variations in the incubator temperature, or to the fact that diffusion in the jar solution was too sluggish. The surface, or effective, layers of the solution would vary with the absence, or varying amount, of shaking which the jar received during the weighing periods.

Thus the following results were obtained over four successive periods with No. 5 sample :—

Period. Hours.	*Rate of Flow.* Grm. per 24 hours.	
Between $499\frac{1}{4}$–$524\frac{3}{4}$	·4200	
„ $524\frac{3}{4}$–$545\frac{3}{4}$	·4350	Average ·422
„ $545\frac{3}{4}$–$576\frac{1}{2}$	·4033	
„ $576\frac{1}{2}$–$646\frac{1}{4}$	·4272	

The averages of these and similar results for plugs Nos. 1 to 4 were taken as giving the rates of flow, which, corrected as for a plug one square inch in cross section, were as follows : -

Plug No.	Length inches.	Vapour pressure conditions at surfaces of liquids in tube and jar equivalent to humidity of 100 per cent. and 0 per cent. Rate of moisture passage grm. per 24 hours per square inch section.
1	2·0	0·143
2	1·5	0·179
3	1·0	0·234
4	0·75	0·282
5	0·50	0·343

Further experiments were made with the same plugs using solutions other than concentrated acid in the jars and desiccators.

Solutions of approximately 20, 30 and 40 per cent. acids were used. The order in which these solutions were used was varied so that, for instance, a plug might be placed over 30 per cent. solution after 20 per cent. solution, and later over 30 per cent. solution after 40 per cent. solution. In the first case the moisture flow would gradually decrease

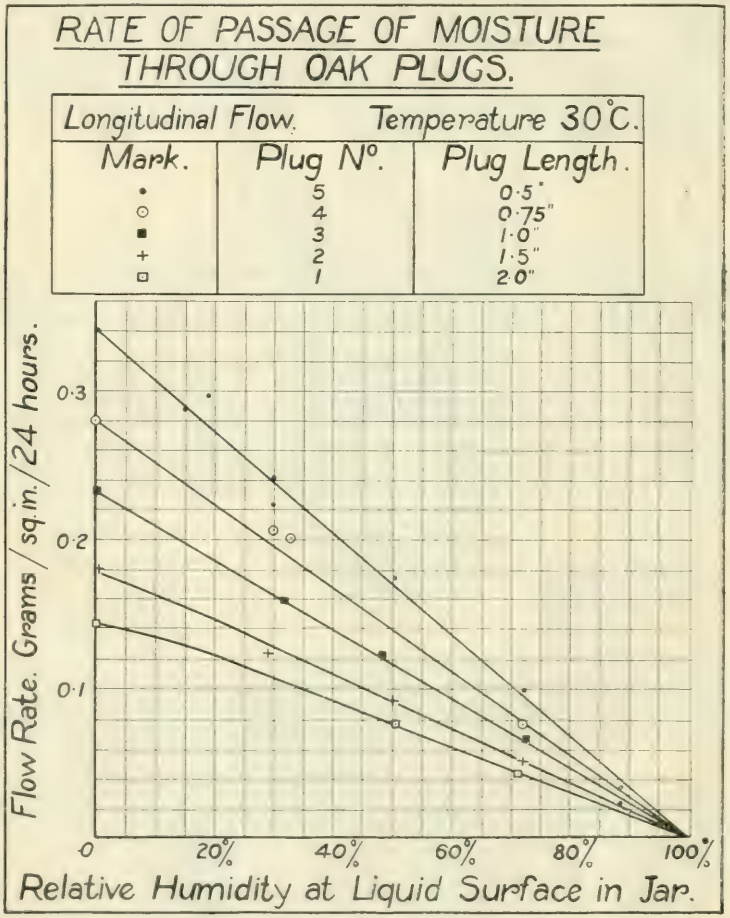

Fig. 2.

to the final constant rate, and in the second, increase to that rate, while the moisture gradient in the plug was becoming adjusted to the new conditions. In the case of these plugs, the final rate of flow appeared to be about the same, from whichever side it was approached.

The results of the above experiments are shown plotted on Fig. 2. Within reasonable limits, the rate of flow is directly proportional to the difference of vapour pressures at the surfaces of the liquid in the sealed tube, and in the containing jar. The cause of such deviation as occurred was not clear at the time of the experiment. Ample explanation is afforded, as will be seen later, by the lack of regard paid to the significance and control of the vapour pressure gradients in the air spaces in the tube and jar, between the faces of the plug and the surfaces of the liquids.

Although outside the scope of this paper, a number of observations were made on plugs, a portion of which had a content above fibre saturated point, and these may be mentioned briefly. In the experiments, a wick dipping in the water of the tube was held firmly against the inner face of the plug. The plugs used were three from the five of the first experiment. The flow rate increased slowly until what appeared to be a constant value was arrived at, in each case.

It is notable that the final flow in the case of each plug showed a proportionate increase over that for content below fibre saturation point, as will be seen from the table below.

Plug No.	Length.	Solution in Jar.	Flow rate grm. per sq. in. per 24 hours.		$\frac{F_1}{F}$
			F. Flow below F.S. Pt.	F_1. Flow with damp wick.	
	(inches)				
2	1·5	Conc. Acid.	0·179	0·312	1·74
4	0·75	do.	0·282	0·487	1·73
5	0·5	do.	0·343	0·592	1·73

Before the completion of the experiments on longitudinal flow described above, six plugs were selected from a piece of green oak of good quality, for the purpose of investigating the rate of flow in a radial and tangential direction. The method of cutting from the piece is illustrated in the attached Fig. 3.

The plugs were treated as in the previous experiments for sealing. Owing to the high moisture content of the timber, difficulty was experienced in making a good joint and frequent inspection was necessary for some time.

The plugs were first placed over a 25 per cent. (by volume) solution of sulphuric acid at 30° C.

It is perhaps worth while to describe the course of the experiment in detail, but only one or two of the plugs need be considered, as the behaviour of all was the same.

The longest and shortest plugs giving radial flow are taken below. At first, the rate of flow was considerable, but it quickly diminished to an approximately constant value. As the plugs were cut from green timber, and one end had been continually in contact with saturated vapour, it was regarded as probable that the moisture content at that end of the plug might still be above fibre saturation point. It was, in this case, conceivable that there might be a tendency of the moisture content at that end to fall to the fibre

saturation point, with a resultant flattening of the moisture gradient in the plug, and a lowering rate of flow. To test this the above experiment was carried on for over a thousand hours after the apparent constant flow had been reached.

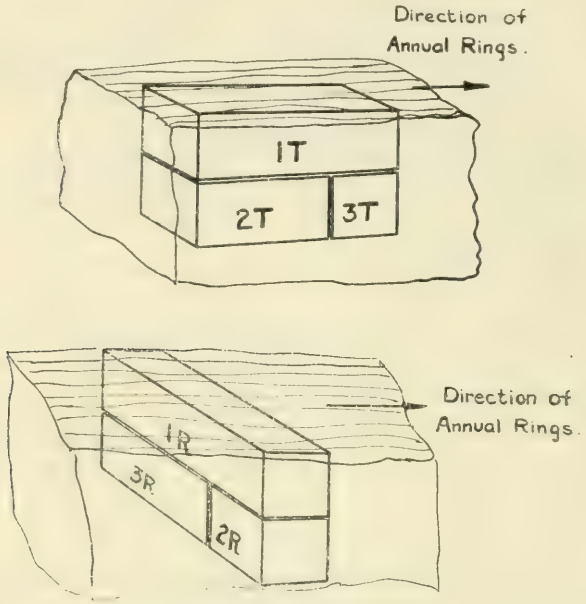

FIG. 3.

No marked reduction of flow rate took place as the following figures show :—

Plug 1R, 1½ in. long, giving radial flow.

Time from beginning of experiments. Hours	Rate of flow. Grm. per 24 hours.	Remarks.
Between 0–20	·192	Decreasing flow.
90–140	·153	
190–236	·110	
357–404	·070	
824–1003	·058	Approx. constant.
1384–1628	·057	No reduction.
1628–1920	·052	Practically no reduction.

Plug 3R. ½ in. long Radial flow.

0–20	..	·218	Decreasing.
71–92	..	·139	
357–400	..	·099	
570–1003	..	·095	Approx. constant.
1482–1628	..	·098	,, ,,
1628–1920	..	·096	No
1920–2040	..	·098	reduction.

At the end of the periods named above, the water in the tube affixed to one plug became exhausted, and inadvertently the supply was not immediately replenished. The rate of flow diminished by degrees, and when the water supply was renewed after a few days and constant flow was again obtained, the value of this was lower than that given above.

Thus with plug 1R a flow rate over 900 hours of ·045 instead of ·056, and with 3R, ·087 instead of ·096 was obtained, and further extension of the dry period with plug 3R gave a flow of ·072 over a similar period.

It was then decided to dry the plugs as a means of ensuring that all portions were below fibre saturation point. The plugs were then placed again over concentrated acid, and later over solutions giving approximately 31, 46, 57, and 72 per cent. relative humidity difference between the surfaces of the liquids in tube and jar.

The resulting flows, which now became reasonably fixed in value whether approached from above or below, are best illustrated by curves, as in Fig. 4.

The following points and difficulties, which arose from time to time, are perhaps worth noting :—

(*a*) There were five types of variation in the rate of flow, as follows :—

(1) When the plug was first put in the jar, as it adjusted itself to the conditions, the rate of flow increased or decreased until it reached an approximately constant value.

(2) There was a slight day to day variation in the flow round this constant value.

(3) It was also found that if the plug was kept in the jar over a long period, the solution being renewed at frequent intervals, however, so as to keep the humidity conditions fairly steady, the rate of flow fell very slowly. No explanation suggested itself at the time of the experiments, but as will be seen later, the cause is the fall in level of the water in the sealed tube, as the moisture escapes through the plug.

(4) Another type of variation in the flow is mentioned above in the description of the experiments on radial and tangential flow. In these experiments, the plugs were green at the start, and several succeedingly lower values were obtained for the flow, as the timber dried out.

(5) The rate of flow fell off, as the jar solution became more dilute.

(*b*) When the plugs were taken from their jars to be weighed, they lost or gained weight whilst on the balance. This was obviated to some extent by shortening the weighing time, by arranging that the necessary weights, so far as could be estimated, should be on the scale pan.

(*c*) There was disturbance due to cooling, etc., of plug, jar and oven during the weighing period. This was reduced by weighing at less frequent intervals, and as under (*b*) above.

(*d*) The temperature of the oven varied slightly, and though the variation was not great, it appeared to cause an appreciable alteration in the rate of moisture flow.

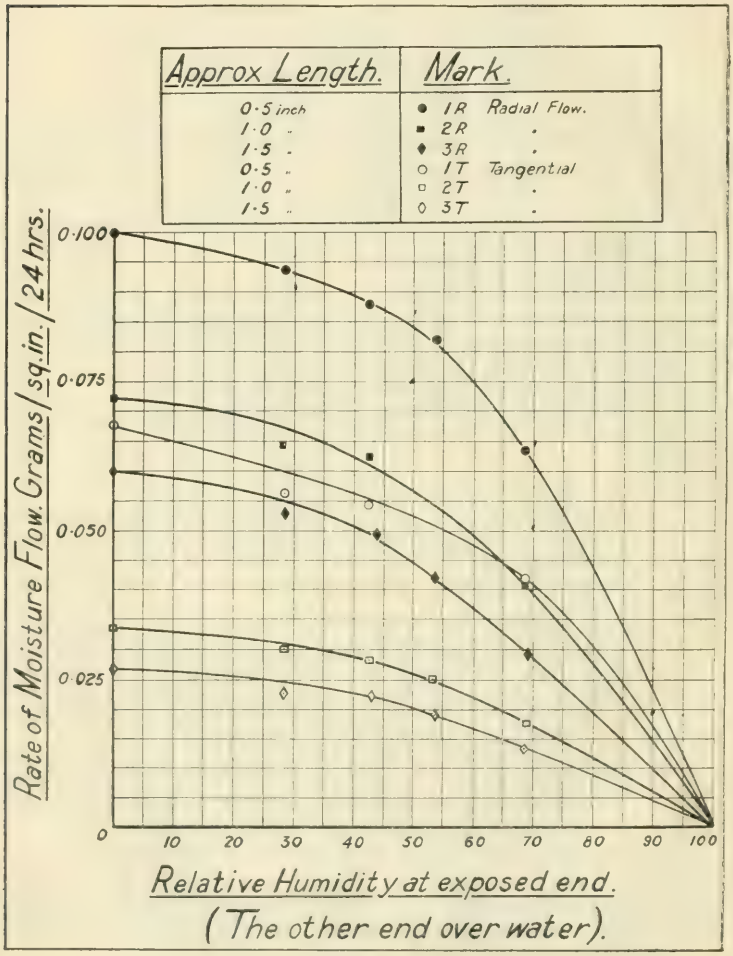

Fig. 4.

(*e*) Leakage into and from the jars was found to be small in general. Resin cerate was used as a sealing material, and was satisfactory at the temperature used.

(*f*) Leakage occurred at times through the sealing of the plug, and constant supervision was necessary.

(*g*) The importance of the vapour pressure gradient from the free face of the plug to the surface of the solution in the jar was not realised until late in the experiments, and at first no attempt at control was made. Only an approximation to desirable conditions resulted from the fact that each plug of the first series was kept in its own jar throughout the experiments, and the jars used were similar in size.

(*h*) The solution in the jars was changed at frequent intervals, where the amount of moisture passing through the plugs warranted. In some later tests, where the escaping moisture caused only a slow change in the strength of the acid solution, the same solution was retained in the jar, and the alteration in the dilution was allowed for in considering the vapour pressure conditions.

An important variation was made in one series of experiments in the use of a fan to promote a circulation across the free faces of the plugs. A closed circulation was produced in the interior of an incubator by a small fan, which sucked air over the surface of a sulphuric acid solution placed in a large shallow dish, and delivered it past a row of five plugs which were placed in the open chamber instead of in a jar. A steady humidity, very close in value to that estimated from the acid solution strength, was maintained, and after a time an even air flow of roughly one foot per second was kept up. Good results were obtained, but these were not more uniform than those from some of the previous experiments in which containing jars were used. Difficulty was found in keeping the fan motor running, especially in the moister atmospheres of the series.

The following summary shows the small range covered by the experiments so far attempted :—

Approximate length of plugs.	Timber.	Direction of Flow.	No. of plugs in series.	Temp.	Humidity at surface of liquid in tube.	Humidity at surface of liquid in jar.
(inches)					(Per cent.)	(Per cent.)
2·0 to 0·5	Oak ..	Transverse ..	5			100 to
1·5 to 0·5	Oak ..	Tangential ..	3			30
		Radial	3	All	All	
				at	at	
0·6 to 0·2	Oak ..	Radial	3	30° C.	100	46 and 30
1·7 to 0·3	Oak* ..	Transverse ..	5			18 to 60
1·5 to 0·3	Ash ..	Transverse ..	4	30° C.	100	100 to 10
		Tangential ..	4			
		Radial	4			
2·0 to 1·0	Beech ..	Radial	3	30° C.	100	53

* This series was carried out in an incubator without containing jars. The results of these experiments will be discussed at a later stage.

Another slight variation of the normal plug experiments, the results and significance of which will be seen later, consisted in using a longer glass tube than usual. The rate of flow was then measured for various levels of liquid in the tube.

Moisture Content Values of Timber when in Equilibrium with Certain Conditions of Temperature and Humidity

A number of experiments to determine the above values were made in the following manner :—

A portion of a thick shaving, 1 in. square and 0·05 in. thick, was cut from an end section, a radial, and a tangential face of a piece of fairly dry oak.

These pieces were kept on a tray in a desiccator over a solution of sulphuric acid of known strength, the whole being kept at a constant temperature of 37° C.

From time to time the pieces were removed from the desiccator, placed quickly into a weighing bottle, and weighed as expeditiously as possible. It was found that after a time the weight of each shaving became constant within a small range of variation.

A series of values were found for the weight of the shavings over solutions of 10, 20, 30, 40, 60 and 100 per cent. sulphuric acid, after which the shavings were allowed to take up moisture by being placed in succession over 60, 50, 20 per cent. solutions, and finally over water. The shavings were then oven dried and the final weight used to calculate the moisture content at various stages of the experiment.

The results are tabulated below :—

Temperature 37° C. Oak Shavings

Solution Strength by volume.	Corresponding Humidity condition approximate.	Moisture Content.		
		Transverse Section.	Radial.	Tangential.
Per cent.	Per cent.	Per cent.		
10	89·5	20·8	22·7	20·0
20	73·3	16·0	16·1	15·7
30	51·5	11·4	11·9	11·4
40	29·3	7·1	9·4	7·9
60	5·6	2·4	3·2	2·6
100	0·0	1·0	1·7	1·0
Re-wetting—				
60	5·6	2·1	2·9	2·1
50	13·5	3·5	3·8	3·4
20	73·3	13·1	13·6	13·3
Water	100	27	29·5	25·9

A further series of tests were made on oak samples at 30° C.

The results are shown as a curve superimposed on a copy of a similar curve published by courtesy of the U.S. Forest Products Laboratory (Fig. 5).

A number of observations were commenced to investigate the effect of previous treatment of the timber on its content value for a particular humidity condition at 30° C.

It is obvious from the above table that the values in re-wetting are lower than those obtained during the drying process.

It was found, too, in spite of the difficulties due to condensation on the samples, that a moderately fixed value, as high as 80-90 per cent. where the initial content had this value, could be kept up in pieces of green oak placed over water. Apparently, however,

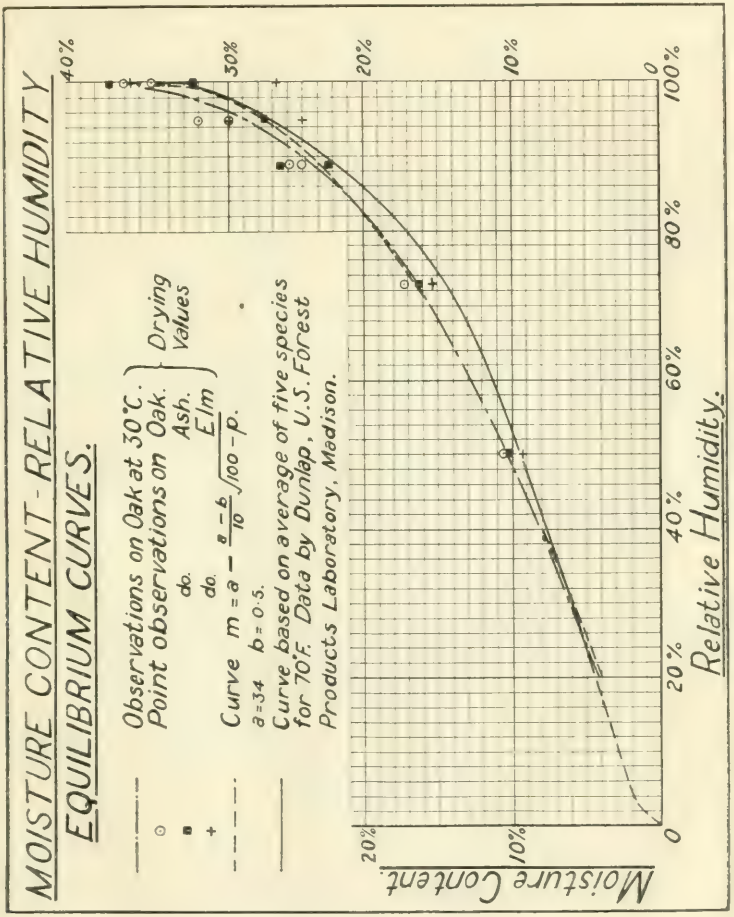

FIG. 5.

if any great amount of this initial moisture were allowed to escape, it could not be replaced from the vapour in the jar.

A number of thin pieces of oak, elm and ash were taken through the operations recorded in order on the table of results below :—

Operation No.	Nature of Operation.	Acid Solution Strength by volume.	Corresponding humidity approx.	Moisture Contents.					
				Oak.		Elm.		Ash.	
				1.	2.	1.	2.	1.	2.
		Per cent.	Per cent.						
1		Water	100	37	35	35·7	24·7	37	31·3
2	Drying ..	5	95	31	29	29	24	35	26·6
3	Drying ..	10	89	24·8	24	25·4	22·2	..	..
4	Drying ..	20	73	17·0	17·2	15·4	15·0	16·1	16·0
5	Drying ..	30	50	10·6	11·1	9·4	9·4	10·2	10·6
6	Re-wetting	20	73	13·9	14·0	12·4	12·6	14·2	13·5
7	Re-drying	25	62	13·1	13·2	11·2	11·4	12·4	12·1
8	Re-drying	30	50	10	10·3	8·8	8·8	9·5	10·0
9	Oven-dried	0	0	0	0	0	0	0	0
10	Re-wetted ..	30	50	8·4	8·4	7·1	7·9	8·1	7·6

It will be seen from operations 4, 5, and 6 that after drying over 20 per cent. followed by 30 per cent. solutions, there is not complete recovery on rewetting over 20 per cent. solution.

The reason why the result of operation 8 should differ from that of 5 is not clear, and is probably due to experimental error, perhaps in solution strength.

Again on rewetting over 30 per cent. after oven drying, there is less moisture taken up by the sample.

Moisture Gradient Experiments

An investigation was also made into the moisture content gradient in a plug such as has been described. The plug was sealed to a tube containing water, and kept under constant conditions until the rate of flow became constant, at 30° C.

The sample was then quickly detached from the tube, and the sealing material cut away by four straight cuts, transforming the plug from one of circular cross section $1\frac{1}{4}$ in. diameter, to one of $\frac{3}{4}$ in. square cross section. This new plug was then cut across into eight or ten approximately equal sections, each of which was put into a weighing bottle, weighed, dried and re-weighed. It was essential that no time should be lost during the cutting process ; the pieces were split off with a chisel where possible ; in other cases, a small dove-tail saw was used for the cutting.

The moisture content obtained was then plotted against the length of the plug, giving a stepped curve, through which a smooth curve could be drawn in to represent the moisture content gradient.

It should be noted that the length of the section or step on the curve was measured after the piece had been oven dried. Except in the case of the plugs where the flow was with the grain, it was necessary to make some correction for the shrinkage which occurred in the length of the small sections on drying, so that some approximation was made to their original length in the plug.

Figures had previously been obtained at 30° C. (see preceding section) of the moisture content-humidity equilibrium points for certain timbers. Using these, new curves were drawn through points representing the equilibrium humidity values corresponding with the content at different points on the original gradient.

These relative humidity or vapour pressure curves—the vapour pressure being expressed as a percentage of the saturation pressure—are shown on eight diagrams attached, Fig. 6 (A to H), as the upper curve in each.

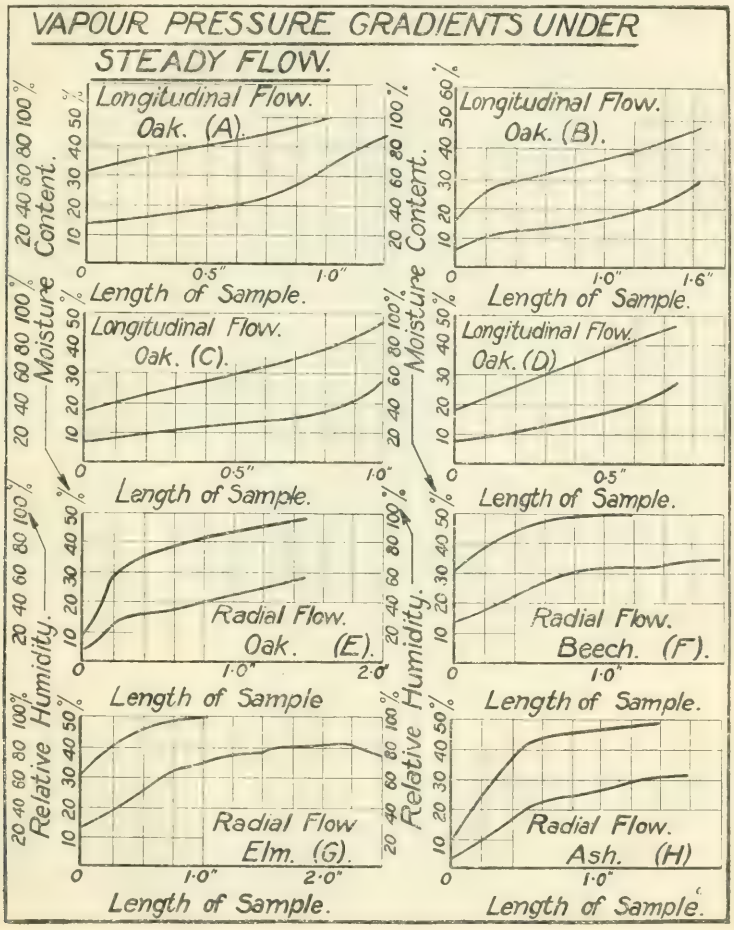

Fig. 6.

The chief difficulty in obtaining accurate results is in the fact that it takes time to carry out the necessary manipulation, during which the various sections take up and lose moisture according to their moisture content condition. The ends of the plug were exposed during the whole of the cutting process, and as these represent the wettest and driest portions, they are chiefly affected. The value of the content found for the ends of the plug must not, therefore, be relied on too much. There does not seem to be any reason, however, why the curve found for the centre portion of the plug should not show, approximately, the true moisture content gradient for the sample concerned. The bulk of the work done was of a preliminary nature, and examples were taken of plugs under different conditions, rather than a related series under the same conditions.

Too few gradients have been examined to lead to any definite conclusion, but the following observations may be recorded.

In the case of flow along the grain in the first oak samples, the vapour pressure gradient below fibre saturation point, although fairly straight, has a curved form, concave upwards for the higher vapour pressure values, and downwards for the lower range. This appears most clearly on Fig. 6 (B).

At first, it was thought that the deviation from the straight line joining the extremities might be explained as due to errors of the experiment, to inaccuracies in the values adopted for the content–humidity equilibrium conditions, or to the fact that the gradient of the plug, at the time of determination, was not stable but changing—adjusting itself to slightly altered end conditions, such as would result from a renewal of the solution in the containing jar.

It was found, however, that the curve was typical of several oak plugs where the flow was along the grain. Moreover, as has been shown above, the chief error in the determination of the moisture contents curve will appear in the end values, the higher of which as determined, will be too low, and the lower too high. An elimination of these errors would, therefore, make the divergence of the vapour pressure gradient from the straight even more pronounced.

It is notable that, in several cases, the point of inflection of the curve occurs at about the same vapour pressure value—between 50 and 60 per cent.

Very few gradients of radial flow have been made, but Fig. 6 (E to H) shows such curves for Oak, Beech, Elm and Ash. The curves bear a strong similarity to each other, both in the general shape of the curve, and the irregularity of its contour. The vapour pressure curves, it will be noticed, are convex upwards.

Only one tangential flow gradient was investigated. The curve in this case was of similar shape to the ones illustrated for radial flow.

The Passage of Air through Oak

In connection with the foregoing experiments, observations were made on the rate of passage of air through a timber plug.

The apparatus used is shown in Fig. 7.

The free mercury column was raised to give a suitable pressure of the air and cause a flow through the plug, observation being made at intervals of the volume of air escaping by reading the burette scale, suitable corrections being made at each interval for pressure and volume, so as to reduce the calculated volume of air passing through the plug to that of air at 0° C. and 760 mm. pressure.

The assumption was made that the rate of flow would be proportional to the pressure difference,

i.e., $\frac{dV}{dt} = K \cdot p_t$ (V being measured at 0° C. and 760 mm. pressure),

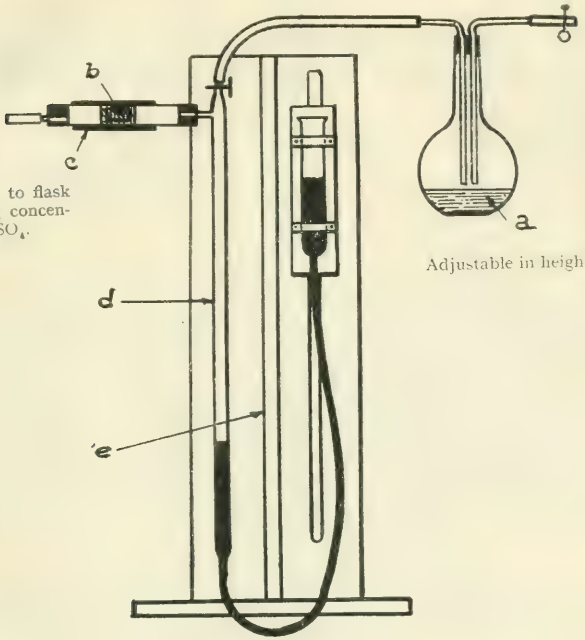

FIG. 7

Reference :—

a Concentrated H_2SO_4.
b Plug.
c Sealing material.
d Burette graduated in c.c.
e Scale graduated in m.m.

and the value of K was found experimentally over various ranges of pressure differences in the case of a plug 9·42 mm. long, 31·6 mm. diameter, the flow being in a radial direction of the oak timber.

T = about 289° C.

V measured in c.c.

p_t in mm. mercury and t in hours.

The following results were obtained :—

Range of pressure on air over atmospheric mm. mercury.	Value of K.	Remarks.
110·5 — 91·5	0·0095	5 per cent. moisture content.
101 — 85	0·0086	Drier.
85 — 29	0·0081	
58 — 45	0·0096*	Same day, *i.e.*, moisture content, approximately the same.
130 — 105	0·0081*	
163 — 126	0·0096	
126 — 45	0·0083	
163 — 120	0·0089	
66 — 26	0·0083	
77 — 65	0·0081	
90 — 30	0·0090	Content estimated at 7 to 8 per cent. Sulphuric acid flasks not used.
130 — 100	0·0102	
69 — 18	0·0109	
74 — 55	0·0103	
77 — 20·6	0·0106	
115 — 3·5	0·0104	

The manner of calculating K from the experimental operations was as follows :—

Let B c.c. be the volume between the plug face and the burette zero reading.
b c.c. be the initial reading of the burette.
X c.c. be the difference in the burette reading from the above after time t.
a mm. mercury be the initial mercury pressure head.
p mm. mercury be the mercury pressure head after time t.
P mm. be the barometric pressure } Assumed to remain constant during the
T° Cent. the absolute temperature } experiment.
V the volume of air between the plug face and the mercury surface in the burette, measured at 0° C and 760 mm. after time t,

$$= \frac{(B + b - X)(P + p) \cdot 273}{760 \cdot T}.$$

Now $p = a - m \cdot X$ where m is a constant for the apparatus depending on the relative size (diameter) of the burette and mercury reservoir tubes. These were taken to be of uniform diameter throughout their lengths :

or $$X = \frac{a - p}{m}$$

Assume $\frac{dV}{dt} = K \cdot p$, where K is a constant, and call

$[(B + b)\, m - a]$ equal to L, which is constant for any experiment.

Then $$\frac{d\,(L + p)(P + p)}{dt} = \frac{760}{273} m \cdot K \cdot p \cdot T.$$

$$\text{or } \left(L + P + 2p + \frac{P}{p}\right) \frac{dp}{dt} = \frac{760}{273} \cdot m \cdot K \cdot T.$$

$$\therefore \quad (L + P) \log p + 2p = \frac{760}{273} m \cdot K \cdot T \cdot t + C, \text{ a constant.}$$

When $t = 0$, $p = a$, and C, therefore, is $(L - P) \log_e a - 2a$.

Hence K is calculable from

$$\frac{760}{273} m . T . t . K = [m(B - h) - a - P] \log_e \frac{p}{a} - 2(p - a).$$

No incubator was available for these experiments at the time, and the temperature could be maintained only approximately constant. Any variation of temperature had a serious effect on the results, as the expansion of the air in the burette caused an immediate alteration in the pressure head.

The impression gained from the rough estimations was that the flow was proportional to the pressure difference, but that the constant of proportionality might be affected by the moisture content of the plug.

* * * * *

In experimenting with oak samples giving flow along the grain, it was found impossible to hold an air pressure, even momentarily, with a plug up to $2\frac{1}{2}$ in. long.

PART II.—A SUGGESTED EXPLANATION OF THE MANNER OF MOISTURE MOVEMENT IN TIMBER AT A CONTENT BELOW FIBRE SATURATION POINT

The following discussion on moisture movement in timber arose from the experimental results obtained, after the completion of the majority of the experiments already enumerated. No opportunity has arisen as yet to confirm the conclusions arrived at by a sufficient number of carefully controlled tests. The movement of moisture in timber with content in excess of the fibre saturation point is not considered.

It is found that a piece of timber placed in an atmosphere, the aqueous vapour pressure of which remains constant, gains or loses moisture as it is necessary to bring its content to a certain value, at which it then remains.

This can be explained by regarding the timber as exchanging water vapour molecules with the surrounding atmosphere, the number leaving the surface in a given time depending on the moisture content, just as in the case of an aqueous solution the number leaving the surface is a function of the concentration, or—to make the case more parallel—the dilution.

If the exchange is unequal the timber will gain or lose moisture, until, assuming that an increase in the content means that more molecules leave the surface per unit time and *vice versa*, the inequality of exchange is removed, when the content remains fixed. It would follow from this that a piece of timber of fixed moisture content can be taken as capable of producing a definite vapour pressure at its surface for any determined temperature.

Passage of moisture, therefore, can be expected to take place in general across the space separating two surfaces with unequal moisture content, for the vapour pressures close to the surfaces will be different, and diffusion of aqueous vapour molecules will occur through the separating medium.

It is known from kinetic molecular reasoning,* and from experimental confirmation, that, when conditions of steady flow in a uniform tube are established, the rate of diffusion of one gas into another is proportional to the rate of fall of its partial pressure in the direction of flow.

* Meyer.—*Kinetic Theory of Gases*.

So that in such a tube, the rate of flow of water vapour between two cross sections, the vapour pressures at which are p_0 and p_1, the total pressures being the same, may be written $K \frac{(p_0 - p_1)}{L} A$, where K is the co-efficient of diffusion of water vapour in air—if air be the separating medium—expressed in suitable units for the temperature considered, L is the distance between the sections, and A the tube cross sectional area. A similar rate of flow would be expected if the sections considered were replaced by surfaces of timber, the vapour pressures corresponding to their moisture content being p_0 and p_1 respectively.

It is assumed below, that diffusion of this type takes place along the experimental plug through spaces between the substance of the timber, and that any cross section, at a distance x from one end, the rate of flow from this source is $K_0 \frac{dp}{dx} . C . A_x$, C representing the fraction of A_x, the total cross sectional area, not occupied by wood substance, and effective for diffusion: the vapour pressure is regarded as uniform over each cross section of the plug, when the flow is steady.

There will also probably be a flow along the wood substance which may be proportional to the vapour pressure fall, the moisture content gradient, or to more complex combinations of conditions. The first two only are considered.

The relation of vapour pressure and moisture content can first be considered from the experimental results.

For any piece of timber, at a given temperature there is a relationship between moisture content and vapour pressure, which may be written $m = f(p)$, m standing for moisture content, and p for vapour pressure, or relative humidity, $f(p)$ for the expression or function of p, which gives the relationship. Without affecting the validity of the argument which follows, the experimental curves obtained may be used to give a more defined, though only approximate, form to the above expression.

It is found that over the greatest part of the range, the curve showing the moisture content—vapour pressure relation is fairly nearly expressed by—

$$m = a - \frac{a - b}{10} \sqrt{100 - p}$$

whence,

$$\frac{dm}{dx} = \frac{a - b}{20\sqrt{100 - p}} \cdot \frac{dp}{dx}$$

The total flow across the section can now be written as—

$$F_x = K_0 \cdot \frac{dp}{dx} \cdot C.A_x + K_1 \frac{dp}{dx} \cdot C_1.A_x \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \text{(i)},$$

if the flow along the wood material is taken as proportional to vapour pressure fall, or—

$$F_x = K_0 \cdot \frac{dp}{dx} \cdot C.A_x + K_2 \cdot \frac{dm}{dx} \cdot C_1.A_x \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \text{(ii)},$$

where the flow depends on the moisture gradient.

The latter gives, substituting for $\frac{dm}{dx}$,

$$F_x = K_0 \cdot \frac{dp}{dx} C.A_x + K_2 \cdot \frac{dp}{dx} \cdot \frac{a - b}{20\sqrt{100 - p}} \cdot C_1.A_x \ldots \quad \ldots \quad \ldots \quad \text{(iii)}.$$

Rewriting the equations—

$$\frac{dp}{dx} = \frac{F_x}{A_x} + (C.K_0 + C_1.K_1) \text{ for the first case, and}$$

$$\frac{dp}{dx} = \frac{F_x}{A_x} + \left(C.K_0 + \frac{(a-b).C_1}{20\sqrt{100-p}} \cdot K_2\right) \text{ for the second.}$$

It is necessary to add that the value of C will vary from point to point along the direction of flow. The variation will be more or less periodic depending on the uniformity or otherwise of the structure of the timber. The true vapour pressure curve, for this reason, will not be a smooth curve, but will consist of a number of recurring short waves. From a practical point of view, it is only possible to determine the general shape of the vapour pressure gradient, *i.e.*, the smooth curve about which the true curve oscillates.

The present discussion will only be concerned with the smooth practical curve, and the mean value of C, which corresponds to the points on this curve.

This value of C, while varying in value for different timbers and directions—tranverse, tangential, or radial, of flow—may be regarded for the moment as a constant, where the structure and section are uniform.

Now, considering the first expression above, the gradient is independent of the value of the vapour pressure, assuming K_1 to be a constant. The vapour pressure gradient in this case should be a straight line for a plug of uniform cross section and structure. This does not satisfy the experimental results on radial flow gradients, and the expression must be regarded as unsatisfactory.

Turning to the second expression,

$$\frac{dp}{dx} = \frac{F_x}{A_x} + \left\{C.K_0 + \frac{(a-b).C_1.K_2}{20\sqrt{100-p}}\right\},$$

the gradient of the vapour pressure will alter from point to point due to the factor

$$\frac{1}{\sqrt{100-p}}.$$

The value of $\frac{1}{\sqrt{100-p}}$ will be least for the smallest values of p, and $\frac{dp}{dx}$ will therefore be greater in a uniform plug for the low values of the vapour pressure.

The general shape of the curve will be convex upwards, with a gradient increasing from the end representing the high values of the vapour pressure.

All the radial flow gradients so far investigated have had this general form.

Moreover, if the term $C.K_0$ be considered large relative to $\frac{(a-b).C_1.K_2}{20\sqrt{100-p}}$, that is, the flow through the interspaces great in comparison with that through the substance, such as may well happen in transverse flow through oak, the gradient will tend towards a straight line as the second factor becomes less significant.

There is one important point to be noted in connection with the curves of moisture gradients obtained practically. These were not, as has been so far assumed, gradients of a plug of timber with uniform cross section. The sample in its initial state, with uniform moisture content, was cut to an even section. Later, when a gradient was set up, due to the experimental conditions, the area through which flow took place would vary from point to point.

In the expression for the gradient, not only will A_x be a variable, but also possibly C and C_1.

These factors taken in consideration might account for the inflected curves of the oak longitudinal gradients.

This point, however, can only be tested by further and more precise experiments.

PART III.—THE EXPERIMENTAL RESULTS

The experimental moisture gradients and content-humidity equilibrium determinations have already been mentioned in relation to the proposed equation of flow.

In discussing the actual measurement of flow through the plugs, longitudinal flow through the oak is considered first.

It has been suggested that in this case, the flow through the wood was small, almost negligible, compared with that through the interstices.

There were several indications from the experiments carried out that this was so, in (I) the comparatively straight vapour pressure gradients obtained; (II) the very free passage of air through such a plug; (III) the flow curves given on Fig. 2; and (IV) an experiment which will be mentioned below. On the other hand, there was evidence that the fibre flow exists in this case in (I) the slightly curved shape of the curves, shown in Fig. 2, of the two longest plugs, and (II) that in a more dense oak the curves corresponding to those on that sheet were all slightly curved.

The expression

$$F_x = A_x \left\{ C \cdot K_0 + \frac{(a-b)\, C_1 \cdot K_2}{20\sqrt{100-p}} \right\} \frac{dp}{dx}$$

may be written

$$F_x = C \cdot K_0 \cdot A_x \cdot \frac{dp}{dx}$$

without serious error for these experiments, *i.e.*, neglecting flow through the wood substance.

Where the flow is steady, the amount of moisture passing each cross section normal to the flow in unit time will be the same. Hence, in a uniform plug, $\frac{dp}{dx}$ will be constant, and the flow per unit area may be written

$$F = \frac{(p_0 - p_1)}{L} \cdot A \cdot K_1,$$

where p_0 and p_1 are the vapour pressures at the ends of the sample, L the length of the plug, A the sectional area and K_1 equal to $C.K_0$.

If P_0 be the vapour tension at the surface of the liquid in the sealed tube, the flow to the sealed end of the plug may be written $K \frac{(P_0 - p_0)}{L_0} \cdot A$, where K is the co-efficient of diffusion of water vapour in air at the temperature and pressure. A similar expression $K_2 \frac{(p_1 - P_1)}{L_1} \cdot A$, will represent the flow from free end to the liquid surface in the jar. It should be pointed out that in some experiments the plug cross section differed slightly from that of the tube. L will not therefore necessarily be the actual length from plug to water surface. In a similar manner, L_1 will depend on the dimensional and positional

relations of the plug and the jar, etc., and will be a virtual rather than an actual length; but is considered to be constant for any one arrangement of plug and jar.

The rates of flow to, through, and from the plug will be the same in the conditions of steady flow.

Hence, for unit cross section area.

$$F = K_1 \frac{(p_0 - p_1)}{L} = K_0 \frac{(P_0 - p_0)}{L_0} = K_0 \frac{(p_1 - P_1)}{L_1}.$$

Writing p_0 and p_1 in terms of F from the last two expressions, and substituting in the first,

$$p_0 = P_0 - \frac{F \cdot L_0}{K_0},$$

$$p_1 = P_1 + \frac{F \cdot L_1}{K}, \text{ and}$$

$$\frac{F \cdot L}{K_1} = p_0 - p_1 = P_0 - P_1 - \frac{F}{K_0}(L_0 + L_1).$$

Hence

$$F = \frac{K_1 (P_0 - P_1)}{L + \frac{K_1 (L_0 + L_1)}{K_0}},$$

or more simply,

$$F = \frac{K_1 (P_0 - P_1)}{L + S}$$

Now if the actual experimental flow values for the five longitudinal plugs are considered, and the values L_0 and L_1, which can be glanced at later, are taken as the same for each plug, the value S can be fixed as follows :—

In plug 1, L = 2 in., F = 0·143, and in plug 5, L = 0·5 in., F = 0·343, $P_0 - P_1$ being 100 in each case.

Hence

$$0{\cdot}143 = \frac{100 . K_1}{2 + S}$$

and

$$0{\cdot}343 = \frac{100 . K_1}{0{\cdot}5 + S}$$

whence

$$S = 0{\cdot}575 \text{ in.}$$

K_1 can now be calculated for each plug using this value.

The values obtained are as follow :—

Plug No.	Length (inches).	Rate of flow grm./day/sq. inch.	K_1
1	2·0	0·143	0·00368
2	1·5	0·179	0·00372
3	1·0	0·234	0·00369
4	0·75	0·282	0·00374
5	0·50	0·343	0·00369

The close agreement of these values is somewhat marred by the fact that no control of L_0 and L_1 was attempted in the experiments, and that they were not kept quite constant.

The value of K_0 is known. In C.G.S. units, the mass of water vapour diffusing in air over unit area in unit time, under unit concentration gradient, is about 0·255 at 30° C.*

* Estimated from KAYE and LABY, *Physical and Chemical Constants*.

The concentration corresponding to saturation at 30° C. is $\frac{\cdot 03215}{10^3}$ grm. per c.c.

The flow therefore where the humidity (or vapour pressure) gradient is $\frac{\text{P per cent.}}{\text{L in.}}$ is $0{\cdot}255 \times \frac{0{\cdot}3215}{10^4} \times \frac{1}{2{\cdot}54} \times \frac{1}{\text{L}} \times \frac{\text{P}}{100}$ per square centimetre cross section per second, or $\frac{0{\cdot}255 \times 0{\cdot}3215 \times 2{\cdot}54^2 \times \text{P} \times 3600 \times 24}{2{\cdot}54 \times 10^6 \times \text{L}}$ per sq. in. per day, or $0{\cdot}0180\ \frac{\text{P}}{\text{L}}$.

K_0 therefore in the present units is 0·0180.

The value of $\frac{K_1}{K_0}$ is 0·205, and this under the assumption made, is the value of C.

$$\text{Now } \frac{K_1}{K_0}(L_0 + L_1) = S, \text{ whence}$$

$$L_0 + L_1 = \frac{\cdot 575}{\cdot 205} = 2{\cdot}8 \text{ in.}$$

Experiments have since been made to ascertain how far L_1 varies for different levels of the plug in the jar, and for different sizes of jar. A wide range of value for L_1 resulted in the different cases with varying jars, but for the same jar, and the same level of the free surface of the plug over the face of the liquid in the jar, L_1 had nearly always the same value.

In the experiments detailed above, the maximum range of variation in L_0 and L_1 is put at 0·2 in. and 0·25 in. Under the assumptions made for transverse flow in oak, it would be expected that K_1 should be constant for all values of $(P_0 - P_1)$. That this is so follows from the curves on Fig. 2, for the rate of flow plotted against $(P_0 - P_1)$ gives a straight line.

Before leaving the discussion of transverse flow in oak, an experiment made to test how far the formula $F = \frac{K_1 (P_0 - P_1)}{L + S}$ can be applied, may be mentioned. An oak plug 1·10 in. long was sealed to a long glass tube, so that the value of L_1 could be varied over a wide range.

If F represents the flow for a distance L_0 between plug and liquid in tube, then, when the difference becomes $(L_0 \pm L_d)$, the new flow F_1 can be determined as follows: –

$$F_1 = \frac{K_1 (P_0 - P_1)}{L + \frac{K_1}{K_0}(L_0 + L_1 \pm L_d)}$$

$$= \frac{K_1 (P_0 - P_1)}{L + S \pm \frac{K_1}{K_0} L_d}$$

$$\frac{L + S}{K_1 (P_0 - P_1)} \pm \frac{L_d}{K_0 (P_0 - P_1)}$$

$$= \frac{1}{F} \pm \frac{L_d}{K_0 (P_0 - P_1)}$$

Starting with the flow for one value of L_a, the other values determined experimentally compared with the estimated quantities as follows :—

Length of L_a	Flow actual.	Estimated
0·87	0·1694	0·1730
1·19	0·1650	0·1680
2·10	0·1549	0·1549
2·45	0·1495	0·1500
3·22	0·1464	0·1441
3·30	0·1415	0·1401

Considering the difficulty experienced in measuring the length L_a, no great importance can be attached to the results, but they tend to confirm the other experimental results quoted to justify the assumption for transverse flow.

It was found that the previous assumption did not quite apply to a second series of plugs of dense oak, nor to the longitudinal flow in ash. The observations in these cases are dealt with as for moisture movement in a direction radial and tangential to the grain.

In this problem there is no negligible term in the expression

$$F = \frac{dp}{dx}\left\{C \cdot K_0 + \frac{(a-b)\, C_1 \cdot K_2}{20\sqrt{100-p}}\right\}.$$

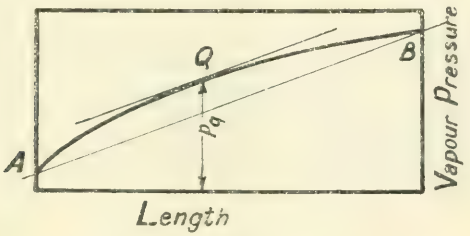

Fig. 8.

The vapour pressure gradient through the plug will be as shown in Fig. 8.

If now p_1 be the vapour pressure at Q, the tangent at which point is parallel to A B, then—

$$\frac{dp_1}{dx} = \frac{p_a - p_1}{L} \text{ and}$$

$$F = \frac{K_a \cdot (p_a - p_1)}{L} \text{ where } K_a = C \cdot K_1 + \frac{(a-b) \cdot C_1 \cdot K_2}{20\sqrt{100-p_1}}.$$

K_a is by no means a constant value, but by assuming it is so where p_a and p_1 are approximately the same, *i.e.*, in each series of plugs which have the same liquids in the tube and jar, the results may be treated as those of the longitudinal plugs, K_a replacing K_1 in that case. Treated on this basis, the experimental results for longitudinal flow through dense

oak and ash, radial flow through oak, ash and beech, and tangential flow through oak and ash, are given in table form below, together with the calculated values of some of the quantities involved.

Dense Oak, Longitudinal Flow

Total Humidity difference $P_0 - P_1$	Estimated Approximate Humidities at faces of plugs of length								F (L ÷ S) for plugs of length				$L_0 - L_1$ ($L_0 = 1{\cdot}7$)	K
	1·68 in.		0·73 in.		0·41 in.		0·32 in.		1·68 in.	0·73 in.	0·41 in.	0·32 in.	in.	
	p_0	p_1	p_0	p_1	p_0	p_1	p_0	p_1						
Per cent.														
60·5	90	42·5	83	44·5	75	46·5	72	47·5	0·231	0·218	0·226	0·232	2·2	0·0037
29	94	71·5	89	71·9	85	72·3	83	72·5	0·139	0·138	0·145	0·144	1·85	0·0049
17·5	96	83	93	83·3	91	83·6	90	83·7	0·086	0·085	0·087	0·085	1·90	0·0049

It will be seen that in the case of the different plugs above, there are different values of p_0 and p_1, and the range $(p_0 - p_1)$ changes from the short plugs to the long ones by a small successive reduction in p_1, and a larger increase in p. It will be seen from Fig. 9 below that unless the vapour pressure gradient is straight, p_0, and therefore K_a, are not actually the same for these plugs.

The variation in the value of p_0 and p_1 in the table above is considerable, and the results must be regarded in this light.

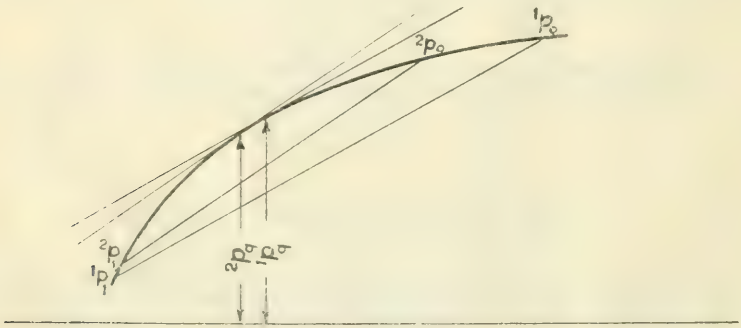

FIG. 8.

Ash, Longitudinal Flow

Total Humidity difference $P_0 - P_1$.	Estimated Approximate Humidities at faces of plugs of length								F. (L + S) for plugs of length				$L_0 - L_1$ ($L_0 = 1{\cdot}7$)	K_a.
	1·50 in.		0·92 in.		0·69 in.		0·30 in.		1·6 in.	0·92 in.	0·69 in.	0·30 in.	in.	
	p_0	p_1	p_0	p_1	p_0	p_1	p_0	p_1						
Per cent.														
100	68	0	57	0	50	0	28	0	0·73	0·74	0·74	0·77	1·7	0·0074
47	84	53	77	53	75	53	55	53	0·40	0·415	0·40	*0·53	1·7	0·0086
28	90	72	87	72	85	72	79	72	0·23	0·23	0·24	0·25	1·7	0·0085
10·3	..	..	..	..	..	..	..	..	0·086	..	0·086	..	1·3	0·0083

* Not used.

The remarks applied to the dense oak plugs above with regard to the values of p_0 and p_1 must be repeated. For instance, in the case for $P_0 - P_1$ 100, p_0 varies between 68 and 28 per cent.

Radial Flow, Oak

Total Humidity difference $P_0 - P_1$.	Estimated Approximate values for plugs of length						F. (L + S) for plugs of length			$L_0 - L_1$ ($L_0 = 1{\cdot}7$)	K_a.
	1·5 in.		1·0 in.		0·5 in.		1·5 in.	1·0 in.	0·5 in.	in.	
	p_0	p_1	p_0	p_1	p_0	p_1					
Per cent.											
100	96·5	39	96	46·5	94·5	63	0·1569	0·1505	0·1569	12·5	0·00155
72	97	50	96·5	54	95	67	0·1177	0·1123	0·1177	8·5	0·0016
57	97·5	61	97	66	95·5	75	0·1072	0·1056	0·1072	8·1	0·0019
46·5	97·5	63·5	97	66·5	95·5	73	0·0857	0·0848	0·0857	5·3	0·0018
31	98·5	73·5	97·5	75·5	96	78·5	0·0548	0·0574	0·0548	3·7	0·0018

For the above table, the values of S were calculated from the values of the $1\frac{1}{2}$ in. and $\frac{1}{2}$ in. plugs. The values of $L_0 + L_1$ are curious, and are perhaps to be accounted for by the fact that the plugs were kept in dessicators, each accompanied by another tangential flow sample of the same length. The results are of doubtful value.

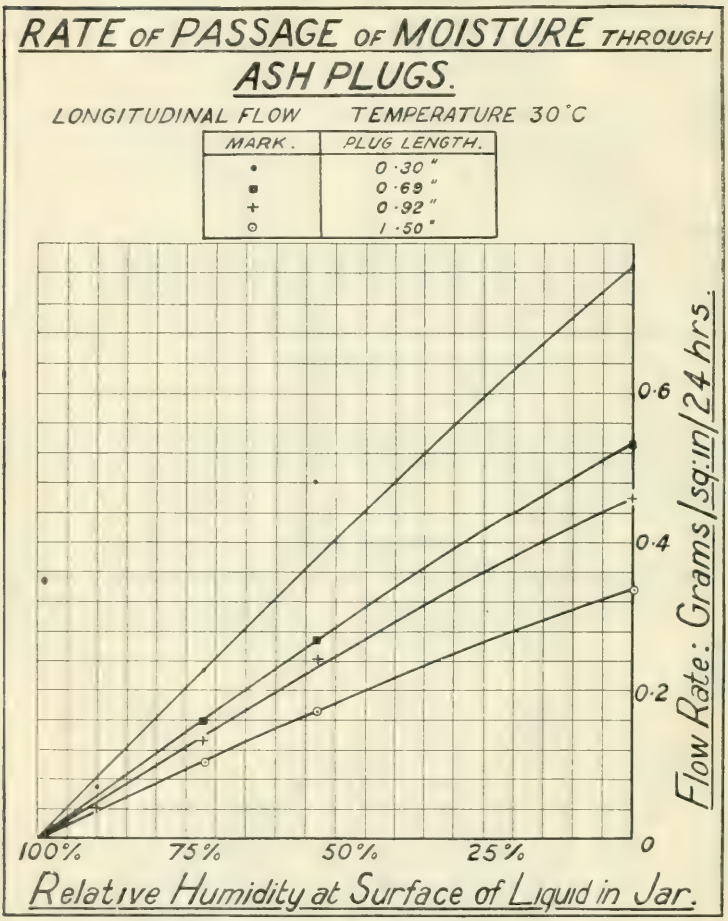
RATE OF PASSAGE OF MOISTURE THROUGH ASH PLUGS.
LONGITUDINAL FLOW TEMPERATURE 30°C
MARK. PLUG LENGTH.
• 0·30"
■ 0·69"
+ 0·92"
○ 1·50"
0·6
0·4
0·2
0
Flow Rate: Grams/sq:in/24 hrs.
100%
75%
50%
25%
Relative Humidity at Surface of Liquid in Jar.

FIG. 10.

Radial Flow, Oak (Dense)

Total Humidity difference $P_0 - P_1$.	Estimated Approximate values for plugs of length						F ($L_0 - S$) for plugs of length			$L_0 - L_1$	K_0
	0·6 in.		0·35 in.		0·18 in.		0·6 in.	0·35 in.	0·18 in.	($L_0 = 1·7$) in.	
	p_0	p_1	p_0	p_1	p_0	p_1					
Per cent.											
46·5	97·5	59·5	96	63	94	67·5	0·0357	0·0363	0·0357	3·3	0·00077
31	97·5	73	96·5	74·5	94·5	77·5	0·0317	0·0313	0·0317	2·6	0·00102

Radial Flow, Ash

Total Humidity difference $P_0 - P_1$.	Estimated Approximate values for plugs of length								F. ($L - S$) for plugs of length				$L_0 - L_1$	K_0
	1·48 in.		0·97 in.		0·73 in.		0·30 in.		1·48 in.	0·97 in.	0·73 in.	0·30 in.	in.	
	p_0	p_1	p_0	p_1	p_0	p_1	p_0	p_1						
Per cent.														
100	96	3·5	95	4·5	94·5	5	87	11	0·084	0·075	0·064	0·070	2·5	0·00072
47	97	55·5	95·5	56·5	95	57	90	62	0·061	0·061	0·054	0·062	2·7	0·00128
28	97	74	96	74·5	95·5	75	92	78	0·054	0·052	0·050	0·052	2·9	0·00187
10·3	98	91·5	97·5	91·5	..	..	96	92·5	0·034	0·033	..	0·032	2·4	0·00322

Tangential Flow, Oak

Total Humidity difference $P_0 - P_1$.	Estimated Approximate values for plugs of length						F. ($L + S$) for plugs of length			$L_0 - L_1$	K_0
	1·5 in.		1·0 in.		0·5 in.		1·5 in.	1·0 in.	0·5 in.	($L_0 = 1$) in.	
	p_0	p_1	p_0	p_1	p_0	p_1					
Per cent.											
100	98·5	8	98	10	96	20	·0441	·0389	·0442	6·5	·00042
72	99	34	98·5	36	97	43	·0367	·0342	·0367	5·8	·00050
57	99	50	98·5	52	97	40	·0400	·0360	·0400	6·6	·00068
46·5	..	..	..	..	..	..	·0298	·0272	·0298	2·05	·00062
31	..	..	..	..	..	..	·0220	·0190	·0220	small	·00065

Tangential Flow, Ash

Total Humidity difference $P_0 - P_1$.	Estimated Approximate values for plugs of length								F (L + S) for plugs of length				$L_0 + L_1$	K_0.
	1·64 in.		0·97 in.		0·65 in.		0·30 in.		1·64 in.	0·97 in.	0·65 in.	0·30 in.	(L_1 = 1) in.	
	p_0	p_1	p_0	p_1	p_0	p_1	p_0	p_1						
Per cent.														
100	96·5	5	94·5	8	92·5	11	88	17	0·081	0·082	0·079	0·070	3·4	0·00080
47	98	55	96	57	95	58	91	62	0·050	0·051	0·051	0·051	3·1	0·00108
28	98	74·5	97	75	95·5	76·5	93	79·5	0·043	0·040	0·044	0·053	3·6	0·00150
10·3	..	..	98·3	92·5	97·7	93·1	96·8	94	..	0·027	0·029	0·027	3·4	0·00268

It will be noticed that except in the Oak tangential and radial flow experiments, where plugs were kept together in pairs, the values of $(L_0 + L_1)$ are fairly constant in each series.

These values too, are in good agreement with the figures estimated from consideration of the dimensions of the apparatus used.

Generally, in each series, the value of K_0 increases with a decrease of the range $(P_0 - P_1)$ of humidity difference. This would be expected to occur under the assumptions made, whether the vapour pressure curve were convex or concave upwards.

Nor will the range of variation of K_0 in any series assist in deciding the true shape of the vapour pressure curve, unless the comparative importance of the two flows, in the fibre and in the interspaces, be known.

For in $K_0 = C \cdot K_0 + \frac{(a-b)\, C_1 \cdot K_2}{2\sqrt{(100-p_0)}}$ if the factor CK_0 be very great relative to $\frac{(a-b)\, C_1 \cdot K_2}{2\sqrt{100-p_1}}$ the value of K_0 will be influenced by variations in P_1 to a very small extent.

To summarize, the experimental work gives no more than a certain evidence in favour of the assumptions made.

There is nothing in the results directly antagonistic to the idea of a dual flow, and the general form of flow equation.

On the other hand, the precise form of this equation, as was stated earlier, may be very much less simple; in fact this is more than likely, if we consider the manner in which the internal structure of the material changes with changing moisture content. The assumed constant C and C_1 of the flow equation are by no means constant actually.

PART IV.—NOTES ON THE EXPERIMENTS AS SUGGESTIONS FOR FURTHER WORK

If the flow can be expressed in terms of the vapour pressure, such as has been suggested, the relationship between the two must appear in the vapour pressure gradient curve of a plug, the section of which is uniform and the flow through which is steady.

The precise determination of gradients therefore would be of great help to the problem.

The experiments on air passage through plugs were commenced with the idea of obtaining some knowledge as to how much gaseous diffusion was possible. They were discontinued owing to lack of suitable facilities. It is still thought that interesting information may be obtained not only on this point, but also, to some extent, on the effect of varying moisture content on the diffusion.

For with varying moisture content, there will not only be a change in the external dimensions of a sample, but also an internal re-adjustment of the proportions of wood substance and interspaces.

The external change can be measured directly. The internal change may be indicated by the air passage experiments.

As regards the moisture passage experiments, it will be seen from the tables of results that these fail in precision from the fact that the values of p_0 and p_1 were not sufficiently well controlled.

If suitable apparatus can be devised to give close control of the end conditions —a difficult, though not insuperable matter—the observations on a number of series of plugs could be used in conjunction with the corresponding vapour pressure gradients to test any form of expression proposed for the flow rate.

In the present experiments, practically only one temperature has been used. It is possible that the change of flow rate with varying temperature may throw some further light on the manner in which moisture moves through timber.

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